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A Spatial Interference Minimization Strategy for the Correlated LTE Downlink Channel

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Abstract—In a downlink transmission, users can benefit from the high capacity gain achieved by transmitting independent data streams from multiple antennas to multiple users sharing the same physical time-frequency resources. This technique is known as multiuser MIMO (MU-MIMO). However, performance of MU-MIMO is sensitive towards propagation imperfections, such as time dispersion and inter-stream interference due to antenna correlation. In this paper we investigate the performance of MU-MIMO operation in 3GPP-LTE downlink transmission by employing a novel multiuser allocation, known as dynamic subcarrier allocation (DSA) that aims to minimize the effect of antenna correlation from the knowledge of the Effective Signal-to-Interference-plus-Noise Ratio (ESINR) metric. The sub-optimal scheme is especially attractive when the number of users is large in highly correlated channel conditions where it is able to minimize the effect of spatial correlation and thereby achieve improved BER performance.

Keywords- correlated channel, ESINR, LTE, MIMO, MU-MIMO, multiuser, self-interference, spatial correlation, spatial multiplexing, subcarrier allocation

I. INTRODUCTION

Over recent years, Multiple-Input Multiple-Output (MIMO) techniques have been increasingly recognised as essential to achieve large capacity gains for future wireless communications, such as 3GPP Long Term Evolution (LTE). LTE operates in several modes of operation, as proposed in [1] in order to achieve high data rates and system capacity. The selection of MIMO transmission depends on the characteristics of the MIMO channel and the system parameters, for example, spatial correlation, time dispersion, availability of feedback and number of users served in a cell.

For scenarios where a large number of users is desired, high capacity gains can be expected from the use of MU-MIMO [2]. In general, LTE supports two modes of downlink operation: SU-MIMO and MU-MIMO, where the former only considers access to the multiple antennas that are connected to single Mobile Station (MS) sharing the same time-frequency resource, while the latter operates by scheduling multiple users on different spatial streams over the same time frequency resource, thus allowing additional diversity to be exploited. MU-MIMO essentially refers to an extended concept of Space Division Multiple Access (SDMA).

Gesbert *et al.* [3] have identified spatial correlation as one of the key issues affecting the MIMO system capacity. The

effect, known as *self-interference*, normally occurs in highly correlated spatial channels. Spatial Multiplexing (SM) is sensitive to self-interference due to the nature of transmission inherent in its architecture. The main idea of SM is to transmit parallel independent data streams over different antennas. However, as the spatial correlation increases, the adjacent antennas becomes a dominant source of interference to the other transmitting antenna, whereby a receiver will retrieve the symbols as the same ‘copy’ from the adjacent receiving antenna, also known as an *interferer*. This will increase the linear dependence of data streams and makes the streams detection and decoding a very challenging task for the receiver, resulting in degradation of capacity gain. A fully correlated MIMO channel can only offer a single effective channel, which is similar to a SISO system, as shown by Shiu *et al.* in [4]. Therefore, designing an appropriate downlink transmission that can adjust smoothly to any level of spatial correlation is desired.

Self-interference can be measured by using the ESINR metric [5], which indicates the quality of the MIMO channel from a knowledge of the self-interference caused by the mismatch between the spatial sub-channels. The proposed DSA-ESINR algorithm is adopted from previous work, as published in [6], where it is shown that the Bit Error Rate (BER) performance is improved as the modulation and coding scheme (MCS) increased in uncorrelated channels. The proposed DSA-ESINR also can offer a balance between BER and fair gain when simulated in extremely correlated channel environments [7]. In this paper, the proposed DSA-ESINR aims to allocate the best subcarrier to users that suffer from ‘severe’ self-interference effect due to high degree of spatial correlation. The DSA-ESINR algorithm is simulated for MU-MIMO and SU-MIMO in the LTE environment for comparison purposes. This paper considers both ideally uncorrelated channels and a worse case correlation scenario where the spatial channel is highly correlated.

This paper is organized as follows. Section II discussed the main relevant aspects of the LTE physical downlink. Section III describes the subcarrier allocation process of the proposed DSA-ESINR technique. Section IV explains the simulation setup and parameters used for the LTE downlink simulation. Section V presents simulation results and analysis and finally Section VI concludes the paper.

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II. LTE NETWORK IN A GLANCE

The first release of LTE witnessed many of the features originally considered for upcoming fourth-generation (4G) systems [8], thus the term 4G is widely used within the industry. The LTE system model and specifications are also aligned with the recommendation from next-generation mobile network (NGMN) [9]. LTE can offer a peak data rate up to 326.4 Mb/s with a 4×4 antenna configuration, a radio network delay of less than 5 ms, improved spectrum efficiency and ‘flat’ network topology designed to reduce cost and simplify network operation.

A. LTE Basic Transmission Scheme

Several transmission bandwidths are possible, ranging from 1.25 MHz to 20 MHz [9]. The system bandwidth is divided into sub-channels, denoted as Resource Blocks (RBs), which are then assigned to different MS for multiple access purposes. Each RB is a group of 12 subcarriers, with constant subcarrier spacing of 15 kHz across all transmission bandwidth (total of 180 kHz in each RB), a normal CP of 4.7μs suitable for most environments and an extended CP of 16.7μs for highly dispersive environments. The physical layer technology employed in 3GPP-LTE in downlink is Orthogonal Frequency Division Multiple Access (OFDMA). The use of parallel narrowband subcarrier transmission, in combination with a cyclic prefix (CP) is effectively robust enough to combat time dispersion without any requirement to resort to advanced and complex receiver equalization. This can simplify the receiver baseband processing, thus reducing the cost and power consumption of MS as a consequence.

B. LTE and Spatial Diversity

MU-MIMO is motivated by results as published by Weingarten *et al.* [10], where it indicates that capacity gain can be achieved when N_t antennas communicate with N_r users. In LTE, MIMO operation can be classified in two modes of operation: SU-MIMO and MU-MIMO. SU-MIMO only considers access to multiple antennas that are connected to a single MS, while MU-MIMO allows a BS to transmit a signal to multiple users in the same time-frequency band simultaneously. MU-MIMO benefits from the knowledge of Channel State Information (CSI) at transmitter.

Recently, a MU-MIMO scheduling and precoding method has been proposed by Rohling and Grunheid [11] for LTE that incorporates an improved interface between the physical and data link control layers in order to provide increased support for on demand Quality of Service (QoS). Contrary to SU-MIMO, limited feedback in MU-MIMO considerably limits the spatial multiplexing gain by inducing the ceiling effect due to quantization error. In order to achieve the full multiplexing gain, the feedback rate should be increased linearly with the SNR with a slope proportional to the number of transmit antennas [12].

C. Unitary Precoding in LTE

One of the key improvements of the LTE spectral efficiency is through the use of a code-book based unitary precoding, also known as per user unitary and rate control

(PU2RC) [13]. A codebook based unitary precoding provides accurate and efficient CSI feedback to the BS, thus allowing channel resources to be allocated to different users in an effective manner without excessive feedback requirements. A DFT-based codebook is proposed for LTE, which consists of a finite number of possible beamforming matrices at both transmitter and receiver. It is generated according to a Fourier basis that provides uniform coverage across a sector. By signaling the preferred matrix, the amount of feedback can be greatly reduced whilst providing considerable performance improvement.

III. SUBCARRIER ALLOCATION WITH INTERFERENCE MINIMISATION

A. ESINR Metric

Random beamforming is considered as a sub-optimal scheme but has the benefit of requiring lower feedback than a ‘full CSI’ method. A unitary matrix, V_r is generated from a predefined codebook and applied to the subcarriers of the OFDMA signal on a RB basis. The mathematical model for a received signal, $Y_{k,s}$ in a downlink LTE system, after FFT and guard removal can be described as follows:

$$\begin{aligned} Y_{k,s} &= H_{k,s} V_{r,s} X_s + N_{k,s} \\ &= U_{k,s} D_{k,s} (V_{k,s})^H V_{r,s} X_s + N_{k,s} \end{aligned} \quad (1)$$

where k denotes the user index, s the subcarrier index, $(\cdot)^H$ denotes the Hermitian function and $H_{k,s}$ is the channel gain between N_t transmit and N_r receive antenna of user k at subcarrier s . $D_{k,s}$ is a diagonal matrix including all the singular values of $H_{k,s}$, $U_{k,s}$ and $V_{k,s}$ are the unitary matrices obtained by applying Singular Value Decomposition (SVD) to $H_{k,s}$. X_s is the $N_t \times 1$ vector of the transmit signal at subcarrier s from the BS and $N_{k,s}$ represents the additive complex Gaussian noise with zero mean and variance. In the MU-MIMO case, $Y_{k,s}$ is distributed among different users, the number of which depends on the number of N_r receivers, provided $N_r \leq N_t$.

The LTE system considered in this paper adopts a linear MMSE receiver, which has the ability to minimise the self-interference whilst not adversely amplifying the received noise. The MMSE filter also has the ability to separate the spatial layer, which allows flexible subcarrier allocation to different user(s). In a 2×2 system, the MIMO channels can be separated into two spatial layers. The received signal, $Y_{k,s}$ is multiplied by the MMSE filter, $G_{k,s}$:

$$G_{k,s} = \left((H_{k,s} V_{r,s})^H (H_{k,s} V_{r,s}) + \text{SNR}^{-1} I \right)^{-1} (H_{k,s} V_{r,s})^H \quad (2)$$

for data stream q at subcarrier s , the user k computes the ESINR:

$$\text{ESINR}_{k,s}^q = \frac{E_s}{\left| (A_{k,s})_{qq} \right| \sigma_{k,s}^2} - 1 \quad (3)$$

where $A_{k,s} = \left((H_{k,s} V_{r,s})^H (H_{k,s} V_{r,s}) + \text{SNR}^{-1} I \right)^{-1}$. E_s denotes the average symbol energy with σ^2 variance and $(\cdot)_{qj}$ indicates the element located in row q and column j .

B. Dynamic Subcarrier Allocation

Each MS calculates the ESINR metric from (3) and feeds back an indication of channel quality to the BS through the feedback channel. According to the LTE specification, this feedback takes the form of the preferred modulation and coding scheme. In this paper, the mapping of the ESINR to/from the modulation and coding mode is assumed to be ideal. Non-ideal cases are recognized as an important subject for future work. From this information, DSA then allocates the best subcarriers to the MS, starting from the user with the lowest ESINR, which suffers from ‘severe’ self-interference effect or poor received signal. The procedure of the subcarrier allocation is described below:

- 1.) The k -th mobile station computes the ESINR metric (3) of the q -th spatial sub-channel and feeds back to the BS.
- 2.) The BS assigns the user with the lowest ESINR to have the next choice of best subcarrier:
 - (a) Generate short list of users, starting with user with least ESINR value, \mathcal{E} for subcarrier n . Find user k satisfying:

$$\mathcal{E}_{k,n}^q \leq \mathcal{E}_{i,j}^q \text{ for all } i, 1 \leq i \leq K$$

- (b) For the user k in (a), find subcarrier n satisfying:

$$ESINR_{k,n}^q \geq ESINR_{k,j}^q \text{ for all } j \in N$$

- (c) Update $ESINR_k^q$, N and $C_{v,k}$ with k and n in (b) according to:

$$\begin{aligned} \mathcal{E}_k^q &= \mathcal{E}_k^q + ESINR_{k,n}^q \\ N_q &= N_q - n \\ C_{v,k} &= n \end{aligned}$$

where N_q is a vector containing the indices of the useable subcarriers, $C_{v,k}$ is the allocation matrix to record the allocated subcarrier, n for user k and v is the cluster size.

- 3.) Go to the next user in the short list in 2(a), until all users are allocated another subcarrier, $N \neq 0$.

From the ESINR metric, the allocation procedure will not allow the allocated subcarrier to be shared with the other users from the interfering spatial layer. This because the channel quality information at subcarrier level, ‘stored’ inside the ESINR metric is unique to every user, thus helping to maximize the fair gain and reduce the complexity of the allocation process.

IV. SYSTEM SETUP AND PARAMETERS

Throughout this paper, an urban macro environment with 500m cell radius, outdoor terminals, 2GHz frequency band and 10 MHz bandwidth are assumed. It is represented by the 3GPP SCM Urban Macro model, with RMS delay spread of 650 ns, excess delay of 4600 ns with Non Line-of-Sight (NLOS) propagation scenario [13]. Details of the LTE OFDMA downlink parameters are summarized in Table I. The proposed DSA-ESINR is simulated across six modulation and coding

schemes (MCS), as summarized in Table II. The channel model is further extended into two correlated channel environments: (1) an uncorrelated channel that represents ideal channel conditions, where the effect of self-interference is very minimal and (2) a ‘highly’ correlated channel, which represents a worse case correlation scenario. The spatial correlation matrix of the MIMO channel, R_{MIMO} , is the Kronecker product of the spatial correlation matrix at the BS and MS, $R_{MIMO} = R_{MS} \otimes R_{BS}$ as proposed by Kermoal *et al* [16]. The proposed correlation scenarios are summarized in Table III.

Full feedback is considered for the MU-MIMO case to achieve the best BER performance. The codebook size of 2 is selected based on the recommendation from the LTE standard [14]. 1000 independent identically distributed (i.i.d) quasi-static Rayleigh distributed time samples per user are used in the simulation. A 2x2 antenna configuration is considered for the simulation but this is readily extendible to higher MIMO orders.

V. PERFORMANCE ANALYSIS

A. BER Performance

Figure 1 illustrates the BER performance for an LTE system employing MCS of QPSK, $\frac{1}{2}$ rate in uncorrelated and fully correlated channels for 10 users. From the BER curves, it can be seen that, as would be expected, the system in the uncorrelated channel has better BER performance. However in a highly correlated channel, MU-MIMO shows significant BER improvement compared to SU-MIMO where the margin of difference is approximately 6 dB at $BER=10^{-2}$.

TABLE I. PARAMETERS FOR THE LTE OFDMA DOWNLINK

Parameters	Value
Downlink Bandwidth	10 MHz
Time Slot/ Sub-frame duration	0.5 ms/ 1ms
Subcarrier Spacing	15 kHz
Precoding codebook size, L	2
FFT Size, N_{FFT}	1024
Useable subcarrier, N_u	600
Number of OFDM symbols per time slot (Short/Long CP)	7/6

TABLE II. MODULATION AND CODING SCHEME

Mode	Modulation	Coding Rate	Data bits/ time slot	Bit Rate (Mbps)
1	QPSK	1/2	7600	15.2
2	QPSK	3/4	11400	22.8
3	16 QAM	1/2	15200	30.4
4	16 QAM	3/4	22800	45.6
5	64 QAM	1/2	22800	45.6
6	64 QAM	3/4	34200	68.4

TABLE III. CORRELATION SCENARIOS

Correlation Modes	R_{MS}	R_{BS}
Uncorrelated	0.00	0.00
Fully Correlated	0.90	0.90

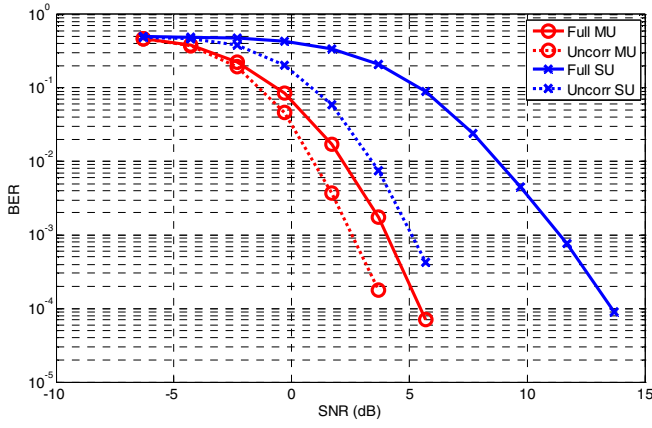


Figure 1. BER performance comparison for 10 users using QPSK, $\frac{1}{2}$ rate.

QPSK modulation is chosen for this simulation due to its characteristic of robustness and its ability to tolerate higher levels of self-interference that makes it suitable for transmission in lower SNR region at the expense of lower transmission bit rate.

B. Multiuser Diversity

Figures 2 and 3 show the BER performance of both SU-MIMO and MU-MIMO with different numbers of users in the highly correlated channel. Generally, as the number of users increases, the BER performance improves for both the SU and MU cases. As the number of users is increased from 1 to 5, the BER performance significantly increases as a result of richer spectral multiuser diversity gains. When the number of users is much larger, e.g. from 10 to 25, it can be observed that the gain of multiuser diversity increases slowly, suggesting that the diversity gain achieves saturation as the number of users increase. This is consistent with theoretical observations made by Tse and Viswanath [17]. The BER performance of MU-MIMO is better than SU-MIMO as the number of users increases. For example MU-MIMO with 10 users offer approximately 6 dB gain at $\text{BER} = 10^{-3}$ compare with the same number of users in the SU-MIMO case. For both cases, it is shown that a small number of users offer minimal BER gain compared to system with 10 or more users. Nevertheless, MU-MIMO has been shown to achieve more gain through the additional dimension of diversity in the spatial domain in both correlation environments by exploiting the spatial layer as an additional dimension for allocating resources.

The BER gain of MU-MIMO can be justified by considering the instantaneous channel response in the frequency domain and the allocated subcarriers, as shown in Figure 4. This result illustrates the multiuser diversity benefit that can be achieved from the combination of DSA-ESINR and MU-MIMO in a highly correlated channel. It can be seen that DSA-ESINR avoids the selection of subcarriers which have similar spectral shape to the interfering adjacent spatial layer, while MU-MIMO providing higher degree of multiuser diversity gain compare to SU-MIMO by exploiting the spatial domain to improve the allocation process. This result also confirms that, besides the ability to mitigate the effect of self-interference, the proposed DSA-ESINR also considers the effect of multiple access interference (MAI).

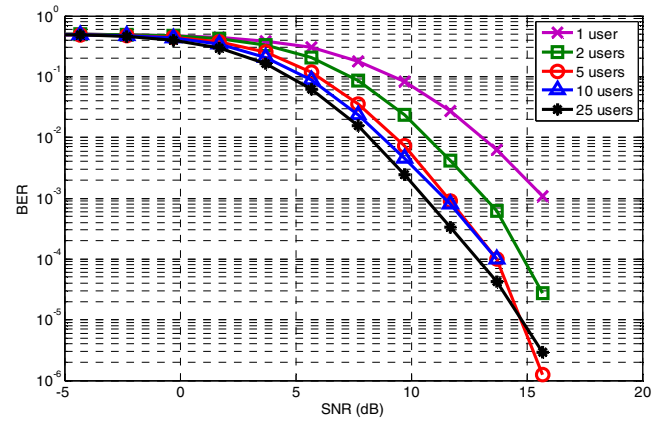


Figure 2. BER performance of SU-MIMO with different number of users.

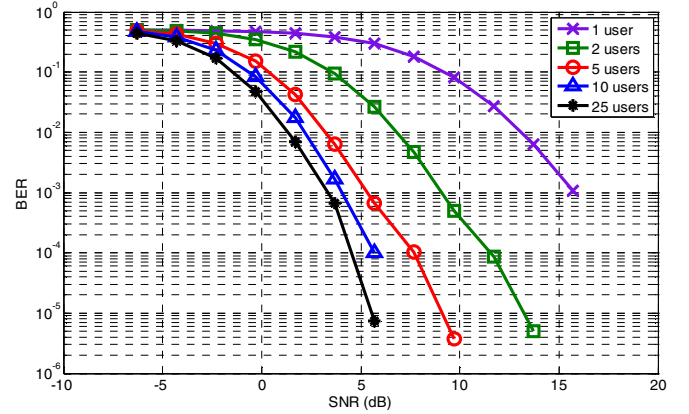


Figure 3. BER performance of MU-MIMO with different number of users.

C. Spectral Efficiency

Figure 5 compares the average bandwidth efficiency of the LTE system in uncorrelated and highly correlated channel environment. Theoretical throughput of a SISO system is plotted as a reference. For both cases, DSA-ESINR for 10 users is considered. From the figure, MIMO systems in uncorrelated channel have better bandwidth efficiency compared with those in highly correlated channels. With the additional spatial diversity that can be exploited, MU-MIMO can provide almost double the throughput across the whole SNR range.

In the case of highly correlated channels, MU-MIMO achieves significant bandwidth efficiency gain when compared to a SU-MIMO. At lower SNR, bandwidth efficiency of a MU-MIMO almost similar to uncorrelated MU-MIMO. This is because the use of QPSK modulation is robust against the effect of channel imperfection, especially channel correlation in this case. At higher SNR, the higher level of MCS found to be vulnerable towards channel degradation. By employing an adaptive modulation scheme, the proposed DSA-ESINR is able to reduce the self-interference effect across all SNR. Considering the correlation environment simulated in the worse case correlation scenario (correlation coefficient of 0.90), the proposed DSA-ESINR is expected to offer higher throughput gain in practical applications in comparison with the results presented in this section.

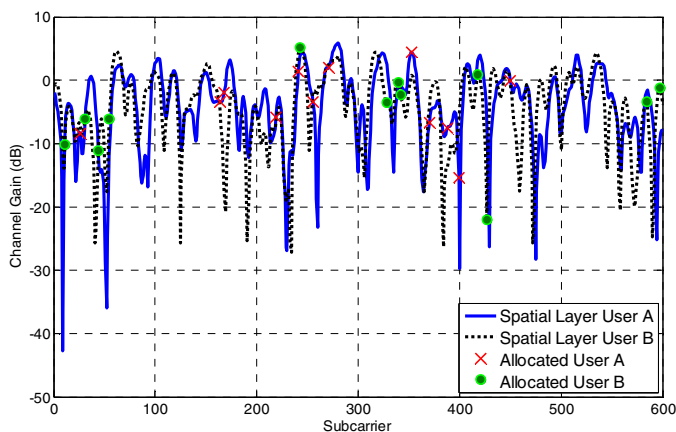


Figure 4. Example of subcarriers allocation in highly correlated channel

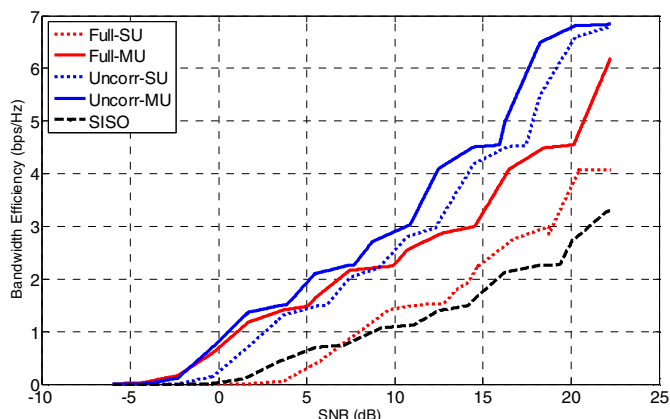


Figure 5. Average throughput comparison between uncorrelated and fully correlated channel

CONCLUSIONS

This paper investigates the capacity performance of MU-MIMO and SU-MIMO transmissions at two different extremes of correlation environments, from the ideal uncorrelated channel to the worst case scenario of full correlation. The analysis is performed on the downlink of 3GPP-LTE OFDMA system and performance of both SU-MIMO and MU-MIMO are presented. A novel subcarrier allocation with self-interference minimization strategy is proposed. It is shown that the proposed DSA-ESINR, in combination with MU-MIMO can improve the capacity when a large number of users are sharing a network with rapidly time-varying channels and suffer from extreme spatial correlation between the antennas. It is also possible to achieve higher capacity gain in practical downlink implementation where the spatial correlation is expected to be much lower than 0.90 used in the simulation.

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